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1. HANDLING QUALITIES AND STRUCTURAL CHARACTERISTICS OF THE HINGELESS-ROTOR HELICOPTER

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SUMMARY

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Several advantages and potential problem areas associated with the hingeless-rotor helicopter are discussed. The extent to which two of the advantages - increased control and damping moments - can be obtained with the hingeless-rotor helicopter is established. The upper limit on the available control and damping moments is associated with the excessive gyroscopic coupling that is obtained with heavy rotor blades. The potential problem areas identified include a structural mode of oscillation very similar to that of a pendulum, which causes undesirably large roll accelerations under certain flight conditions, and large cyclic chordwise bending moments that occur during severe maneuvers (the primary structural problem of concern). Solutions are proposed which should eliminate future concern with these problems.

Author

INTRODUCTION

The hingeless rotor is a configuration that will be seriously considered during new rotary-wing-aircraft design studies. Potential design advantages appear to offset the less complete general knowledge and development history that is associated with semiarticulated or fully articulated rotors. Although a possible substantial reduction in hub drag, a reduction in hub complexity, and a reduction in mechanical maintenance are important considerations favorable to utilizing the hingeless-rotor design, the increased control and damping moment capability, as well as good stability characteristics, may become dominant factors in the choice of a rotor configuration.

It is the objective of this paper to take a critical look at some of the characteristics that result from using a hingeless rotor. The Langley Research Center has conducted flight investigations with two hingeless-rotor helicopters to determine these characteristics. The flight investigations have identified several potential problem areas: an undesirable gyroscopic coupling during maneuvers which adversely affects the aircraft handling qualities, a structural mode of oscillation very similar to that of a pendulum which causes undesirably large cyclic roll accelerations to the pilot under certain flight conditions, and, finally, large cyclic chordwise bending moments during severe maneuvers, the primary structural problem of concern.

These problem areas are different from those that have previously been encountered with articulated rotors, but with full awareness of these problem areas, the designer can eliminate them from future aircraft.

SYMBOLS

C	factor in blade lock number, $\dfrac{(\text{Slope of lift curve})}{\left(\dfrac{\text{Cross-sectional area of blade}}{\text{Blade maximum thickness} \times \text{Blade chord}}\right)} \times \dfrac{\left(\dfrac{\text{Blade aspect ratio}}{\text{Blade thickness ratio}}\right)}{\left(\dfrac{\text{Radius of gyration of blade}}{\text{Blade radius}}\right)^2}$
r	radial distance to blade element
R	blade radius
V	airspeed, knots
ρ_a	mass density of air
ρ_b	mass density of blade
ψ	blade azimuth angle measured from downwind position in direction of rotation, degrees

FLIGHT INVESTIGATIONS

The Langley Research Center has conducted flight investigations with the two hingeless-rotor helicopters shown in figure 1. The first investigation was with a Bell H-13 helicopter for which the rotor was modified to a rudimentary hingeless-rotor design by cantilevering three nearly standard blades from a massive central hub. The remainder of the aircraft was essentially a production H-13. The second investigation, which is currently in progress, is being conducted with the Lockheed XH-51N, an experimental helicopter designed to demonstrate the potential of the hingeless rotor.

ROTOR MOMENT CHARACTERISTICS

The rotor moment characteristics are discussed first because of some limitations on control and angular-velocity damping moments that occur as a function of blade Lock number. The relative hovering control moment available (sea-level condition) with the three primary classes of rotors is plotted as a function of the blade Lock number in figure 2. The blade Lock number is the ratio of the air density ρ_a to blade density ρ_b multiplied by a factor C which includes the mass distribution and the blade planform along the blade radius. The control moment of figure 2 was obtained for rotors having the same value of the factor C. Typical values of blade Lock number range from below 4 to over 12, where 4 denotes a heavy blade and 12 denotes a light blade - that is, increasing Lock number indicates decreasing blade weight.

The reference used for comparison of the rotors is the control moment of a rotor with the flapping hinge at the center of rotation and with a rotor height above the aircraft center of gravity equal to 0.3 times the blade radius. The mean blade lift coefficient was assumed to be 0.4. The control moment per unit of cyclic blade pitch is presented for the hingeless rotor and for a rotor with the flapping hinge at 4 percent of the rotor radius, which is typical of offset-hinge rotor design. The rotor height and mean blade lift coefficient were assumed to be constant for all three configurations. The large increase in control moment available due to cantilevering the blade from the rotor hub is apparent throughout the Lock number range. A flapping-hinge offset from 12 to 16 percent would be required to supply the same available control moment.

The effect of density altitude on the hovering control moment of the three configurations is shown in figure 3 for sample values of sea-level blade Lock number. A separate example for the rotor with a 4-percent flapping-hinge offset and a sea-level blade Lock number of 12 is not shown because the effect is almost the same as that of the rotor with the central flapping hinge.

Similar increases in the hovering angular-velocity damping moment are shown in figure 4 through the use of the hingeless-rotor helicopter. The same three classes of rotors are again compared. As was the case with the control moment, a flapping-hinge offset from 12 to 16 percent would be required to supply the same available damping moment.

The effect of density altitude on the hovering angular-velocity damping moment of the three configurations is shown in figure 5 for sample values of sea-level blade Lock number. A separate example for the rotor with a 4-percent flapping-hinge offset and a sea-level blade Lock number of 12 is not shown because the effect is almost the same as that of the rotor with the central flapping hinge.

Since it is presumed that using very high values of control and damping moment will provide a "tight" control system and the tight system will result in superior handling qualities, the information supplied in figures 2 and 4 indicates that designers should attempt to use blades with low Lock numbers based on sea-level conditions. However, this reasoning disregards the effect of the blade Lock number on gyroscopic coupling.

In figure 6 the ratio of the gyroscopic moment to the angular-velocity damping moment is presented as a function of blade Lock number for typical hingeless-rotor designs in hovering. The gyroscopic moment is the moment developed perpendicular to a commanded angular velocity and is divided by the damping moment that would oppose the gyroscopic moment. The solid-line curve indicates the gyroscopic moment for typical hingeless-rotor designs. Calculated sea-level values of gyroscopic moment for the XH-13N and XH-51N are plotted on this curve. A flight investigation of this type of coupling during rapid rolling maneuvers (refs. 1 and 2) has indicated that values of this ratio in excess of 0.3 in either direction result in unsatisfactory handling qualities and values of this ratio in excess of 0.5 result in unacceptable handling qualities. It is emphasized that the maneuver task that indicated a problem is a rapid rolling maneuver in which excessive longitudinal coupling occurs. The point to be made is that, in order to reduce this coupling to an acceptable magnitude, the blade Lock number should be above 5 for all density altitudes. For a hingeless rotor designed to operate up to a density altitude of 15,000 feet, the blade Lock number at standard sea-level density should be 8 or above. Compromise on this point will depend upon the availability of control devices capable of eliminating gyroscopic coupling.

The extent to which direct control coupling (a pitching control moment accompanying roll control displacement and vice versa) may be used to offset gyroscopic coupling has been briefly investigated with the variable-stability helicopter described in reference 3. It appears from these tests that direct coupling up to about 25° can be used to reduce the effects of the gyroscopic coupling. For a gyroscopic coupling level which was considered to be acceptable only for an emergency condition where gross maneuvering would be restricted, the introduction of direct coupling improved the handling characteristics to a level which was acceptable for maneuvering but still had some unpleasant characteristics. However, for larger angles of direct coupling, the direct coupling becomes a problem in its own right in that lateral control inputs during roll reversals produce an abrupt jerk about the pitch axis. It should be noted that the level of control power and damping used in this investigation was much lower than that typical of hingeless-rotor helicopters. The extent to which higher control power and higher damping would limit the improvement which could be obtained from the application of direct coupling is not known.

The restriction on gyroscopic coupling is not limited to the hingeless rotor. If an articulated rotor with flapping-hinge offset from 12 to 16 percent were used to obtain the same order of magnitude of control and damping moments, undesirable gyroscopic coupling of the same order of magnitude as that shown in figure 6 would again be present.

Unsatisfactory gyroscopic coupling was obtained for the XH-13N as illustrated by the time history of figure 7 showing a lateral step control input and the resulting aircraft response. The calculated response shows reasonable agreement with the measured response, considering that the calculated response is based on a simple first-order two-degree-of-freedom analysis (ref. 2).

Although the coupling illustrated by figure 7 was objectionable, the tight control response, as indicated by rapid attainment of the final velocity, was recognized by pilots as resulting in an improvement in overall handling qualities. In particular, the high damping contribution provides positive maneuver stability throughout the speed range of the hingeless-rotor XH-13N.

As shown in figure 6, gyroscopic coupling would not be expected to be a problem with the XH-51N helicopter because of its relatively high Lock number.

This prediction is verified by the time history shown in figure 8 which indicates nearly a pure roll response to a lateral control input for the XH-51N. In addition, the XH-51N control system does provide some short-term attitude stability which may further reduce any gyroscopic effects (ref. 4).

PENDULUM MODE OF OSCILLATION

The prominent feature of the time history of figure 8, other than the tight response, is the roll velocity oscillation, which indicates that the lateral pendulum mode has been excited. The lateral pendulum mode is frequently excited in the XH-51N by control motions; however, for normal maneuvering, the pilot is not bothered by the oscillation, as he is apparently unable to separate it from normal rotor vibrations. The response of the XH-51N, even with the pendulum mode oscillation, is considered by the pilots to be good and near optimum for hovering. However, the pendulum mode does not always stay below the threshold of the pilot's awareness. A flight condition in which the pendulum mode was excited because of external disturbances is shown in figure 9.

Time histories of the angular velocities and vertical acceleration of the XH-51N while flying in moderately heavy turbulence at 100 knots are shown in figure 9. The lateral pendulum mode shape is illustrated by the highly exaggerated sketches at the top of the figure. The high angular accelerations of the pendulum mode, as indicated by the steep slopes of the rolling velocity trace, provide a very rough ride for the pilot. The roll attitude disturbances, the area under the angular velocity curve, are only about $\pm 1/2^{\circ}$ and are small enough not to be noticeable to the pilot.

Two solutions to this problem are proposed. The first solution is suggested by the sketches at the top of figure 9. Because the oscillation is primarily a rotation of the fuselage against the rotor spring, the addition of a small wing may supply sufficient aerodynamic damping to provide a smoother ride for the pilot. A second solution is to provide vibration isolation of a major part of the fuselage, particularly that portion containing the pilot and passengers. Some limited success along this line was obtained in isolating the pendulum mode of the XH-13N by a random change in the pylon mount stiffness (ref. 2).

STRUCTURAL LOADS

Some of the highlights of the flight investigations in the area of rotor-system structural loads are presented in this section. Because of the basic difference in the aeroelastic characteristics of the hingeless rotor as compared with those of the conventional articulated designs, the objective of the investigations was to identify potential problem areas and to evaluate a simplified analytical treatment that would be useful for preliminary design purposes.

During the flight investigations the rotor and control-system structural loads have been monitored for a wide range of ground and flight operating conditions. Although interesting results have been obtained, the following discussion emphasizes the area of primary concern - that of blade-root structural bending moments developed during rapid maneuvers.

The sensitivity of blade flapwise and chordwise bending-moment amplitudes to maneuvers was indicated in the results of the XH-13N flight investigation. As an example of this situation, a typical time history of a rolling maneuver at 70 knots with the XH-13N is shown in figure 10. The aircraft rolling velocity, blade-root chordwise bending moment, and blade-root flapwise bending moment are plotted over a 6-second interval. The blade response is seen to be primarily one cycle per rotor revolution. The maximum amplitude of the cyclic chordwise bending moment is so large that maintaining this maximum load level would result in a 10-hour fatigue life.

An overall comparison of the results of the flight investigations of the XH-13N and XH-51N to date is shown in figure 11. Nondimensional blade-root cyclic bending moments, flapwise and chordwise, are presented as a function of aircraft velocity. The cyclic moments are nondimensionalized by dividing by the 1 g blade lift moment $\left(\frac{3}{4} R \times \text{Weight of aircraft}\middle/\text{Number of blades}\right)$. The maximum cyclic moments obtained during maneuvers and the level flight loads are indicated for each of the aircraft. The maneuvers were performed at the maximum angular-velocity capability of the respective aircraft - that is, full available control was used. It can be seen from figure 11 that the maneuver loads are the most critical throughout the speed range shown and that the chordwise cyclic moments are more sensitive to maneuvers.

A parallel goal of the investigation was to determine what analytical method would be adequate to handle the calculation of hingeless-rotor maneuver loads and rotor control-moment and damping-moment capabilities. The approach used was to determine the minimum modification required to extend the simple hinged-rotor analysis to the hingeless-rotor case. The basic objectives were (1) to gain some insight into the parameters that contributed to the buildup of loads in maneuvers and (2) to verify an analytical technique that would be useful in preliminary design studies.

The maneuvers primarily affected the first-mode blade response in both the flapwise and chordwise degrees of freedom. Therefore, the analysis of the hingeless rotor was handled by utilizing the simplified concept of a virtual offset-hinge blade with spring restraint at the hinge. This concept is described in reference 5.

Figure 12 shows the equivalent offset-hinge blade used in the analysis. The normalized displacement of the blade is presented as a function of the radial blade station. The actual first mode shape of a cantilevered blade is shown as the dashed line, and the equivalent hinged-blade mode shape is shown as the solid line. The virtual-hinge offset required for equivalence is approximately 8 to 10 percent of the rotor radius. A virtual spring at this point, the stiffness determined from the structural stiffness of the cantilevered blade, completes the equivalent system. The equivalent system then provides the correct flapping and lead-lag angles and gives moments at the center of the rotor equivalent to the moments of the cantilevered blade. The moment characteristics shown in figures 2 to 6 were calculated by using this equivalent system to determine the rotor hub moments.

The simplified analysis using the equivalent system was applied to a number of the maneuvers with the XH-13N. Unstalled blade-section aerodynamic characteristics were used, and the main objective was to find out what parameters contributed to the buildup in chordwise moments. In general, it was determined that the particular combinations of blade cyclic flapping and feathering during the maneuver were the primary factors in the buildup of chordwise moments. An example of the results obtained from an analysis of the chordwise moments in a hovering maneuver are shown in figure 13 which is a time history of the amplitude of the cyclic chordwise bending moment and the blade azimuth position where the positive peak moment occurs. The time interval, 5 seconds, covers approximately 30 rotor revolutions. The calculated moment amplitude and blade azimuth position agree quite well with the measured data. The agreement is good because the response of the XH-13N was essentially one cycle per rotor revolution.

The same analysis was applied to a rapid maneuver at 70 knots for the XH-13N and, in general, agreement was obtained. In the XH-51N flight investigation the general behavior of blade structural loads in maneuvers shows the same trends as in the investigation with the XH-13N. However, a large amount of three-cycle-per-rotor-revolution response is present with the XH-51N, which cannot be handled by this simplified approach. The higher mode response of the XH-51N is due to insufficient separation of the second flapwise bending mode and the three-per-rotor-revolution forcing function. This problem, not unusual with rotary-wing aircraft, can be eliminated by a relatively minor change in the blade mass distribution.

Work is continuing in order to evaluate various means of alleviating the tendency for blade-root cyclic-bending-moment buildup in maneuvers. The theoretical analysis suggests three approaches that warrant consideration. They are as follows:

(1) The moments can be reduced by the elimination of gyroscopic coupling by means of light blades.

(2) The moments can be alleviated by rotor unloading (or operating at reduced rotor mean lift coefficients) because of the reduced collective and cyclic feathering trim requirements for compound operation.

(3) A more direct means of reducing the moments in maneuvers is to introduce chordwise flexibility into the blade.

The third approach is verified by the results of a joint NASA-Lockheed-U.S. Army hingeless-rotor dynamic-model investigation, which are shown in figure 14.

The top curve of figure 14 is for a conventional blade similar to that on the XH-51N or the XH-13N. Introducing chordwise flexibility at the blade root equal to the level of flapwise flexibility substantially reduced the moments. A further reduction was obtained by providing chordwise flexibility along the entire blade span. The theoretical analysis indicates that this reduction in cyclic moment will also be obtained for maneuvering. The proper application of this approach is imperative in order to avoid potential problems of ground and air resonance (ref. 6).

CONCLUDING REMARKS

Results of flight investigations with two experimental helicopters have indicated that problem areas different from those encountered with the articulated rotor occurred with the hingeless rotor. Three problem areas associated with the hingeless-rotor helicopter have been identified. These problem areas and proposed solutions are as follows:

1. Undesirably large gyroscopic coupling is found to occur with hingeless-rotor helicopters having low blade Lock numbers. Two solutions are proposed: (a) utilizing blades with high blade Lock numbers (or lighter blades) and/or (b) providing a control feedback device or direct control coupling capable of reducing the adverse effects of gyroscopic coupling.

2. A structural mode of oscillation very similar to that of a pendulum causes undesirably large cyclic roll accelerations to the pilot under certain flight conditions. Two solutions are proposed: (a) providing roll damping with a small wing and/or (b) providing vibration isolation of the pilot and passengers.

3. Large cyclic chordwise bending moments occur during severe maneuvers. Two solutions are proposed: (a) utilizing blades with the level of chordwise stiffness equal to that of the flapwise flexibility and/or (b) designing the rotor to operate at reduced rotor mean lift coefficients.

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Figure 1

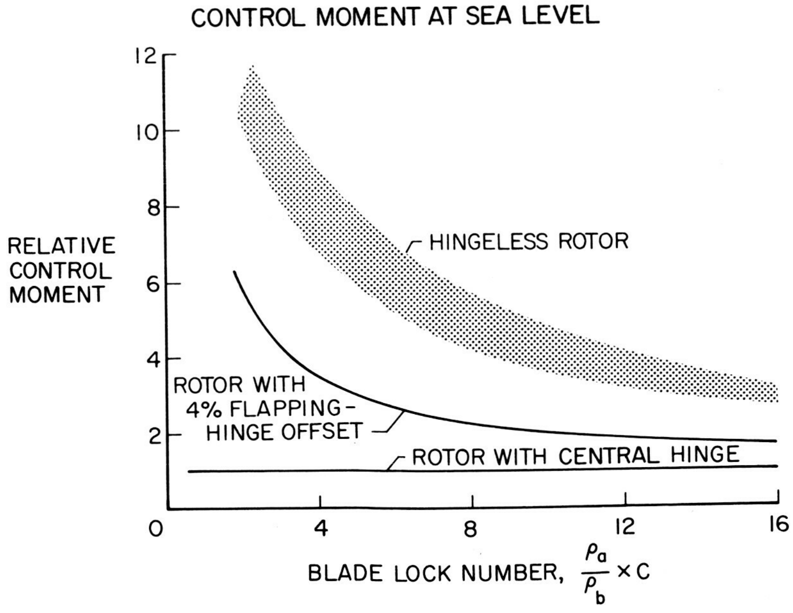


Figure 2

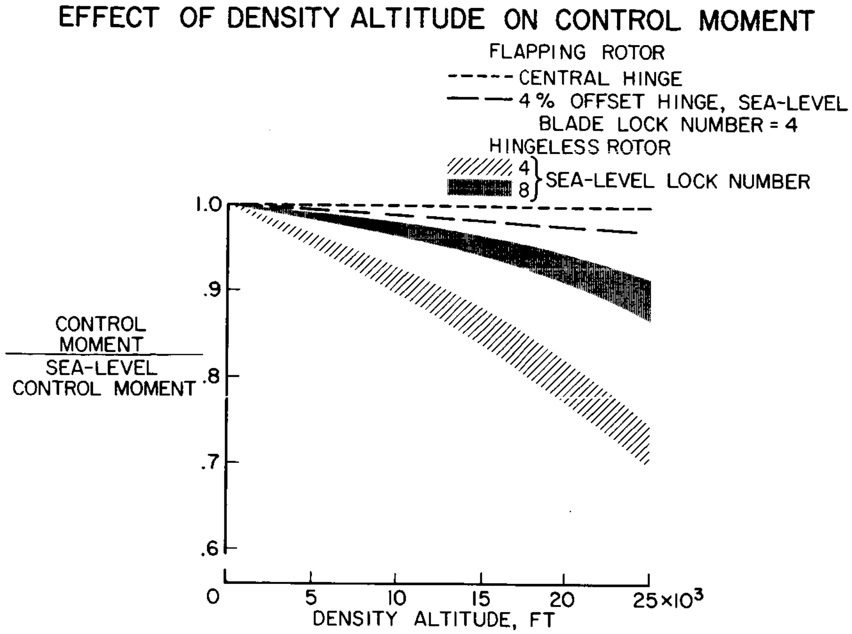

EFFECT OF DENSITY ALTITUDE ON CONTROL MOMENT

Figure 3

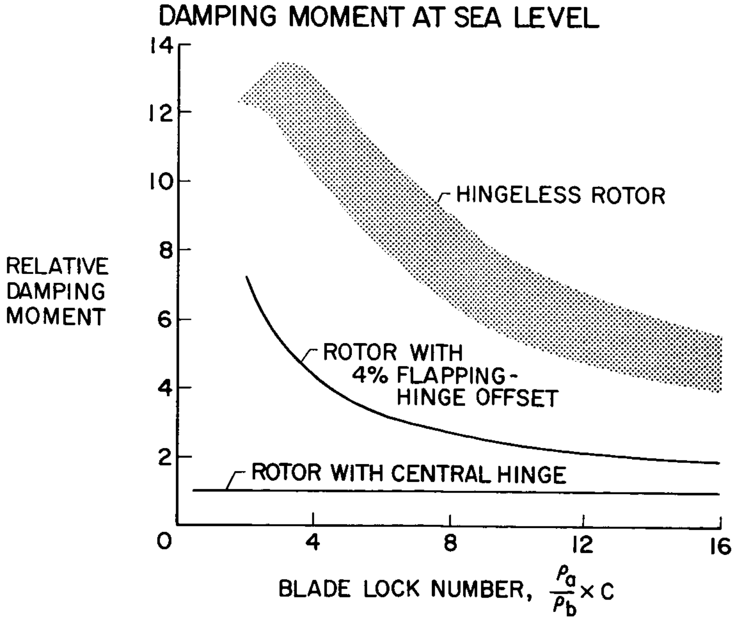

DAMPING MOMENT AT SEA LEVEL

Figure 4

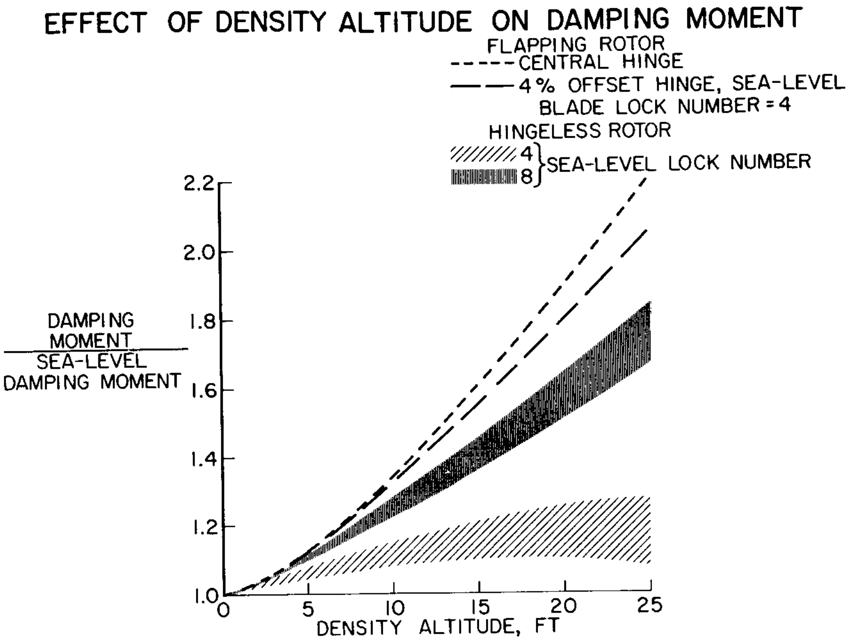


Figure 5

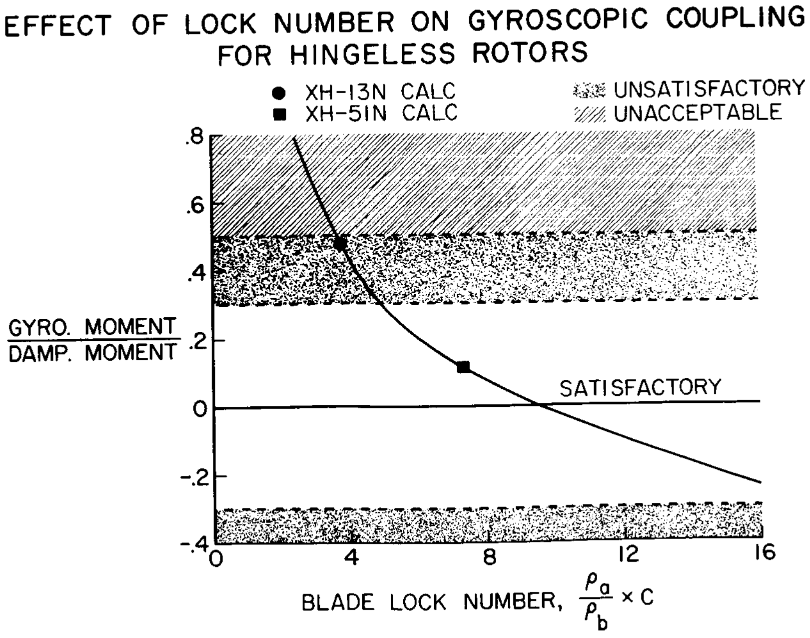


Figure 6

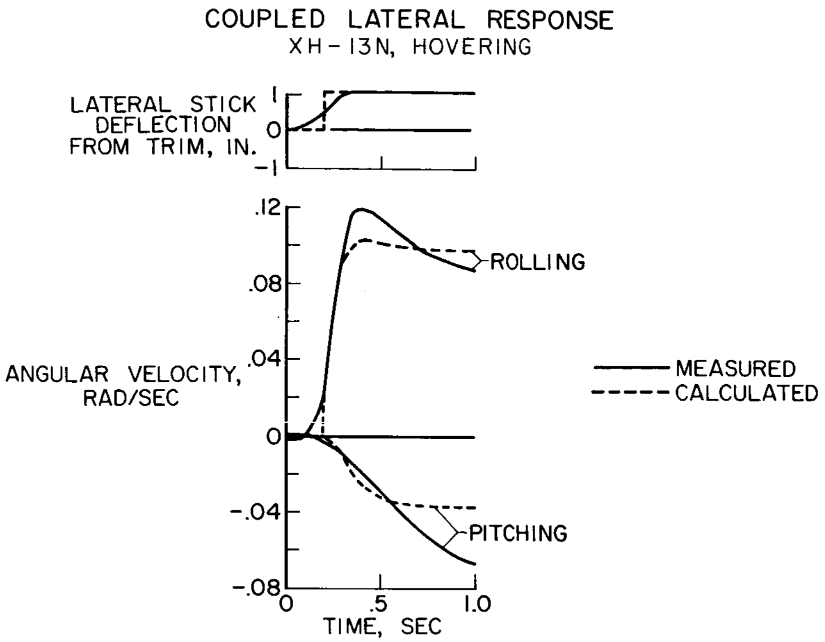


Figure 7

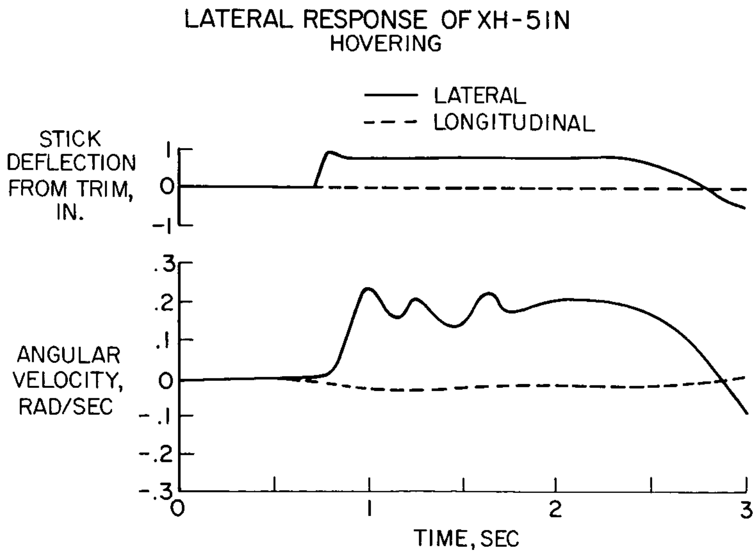
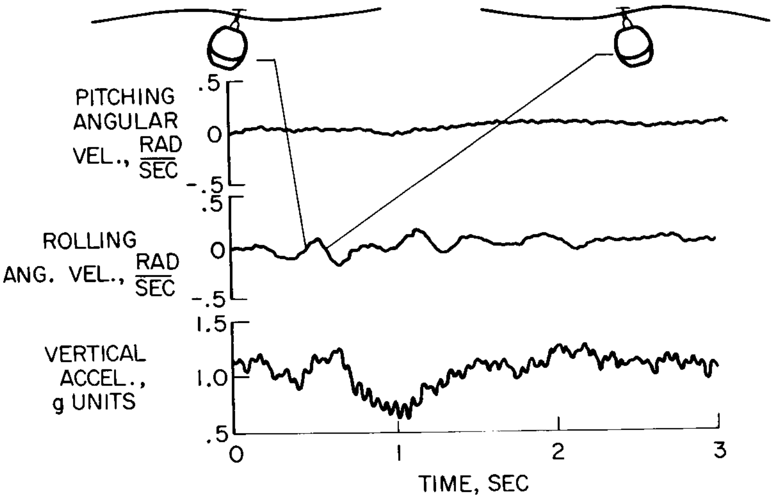
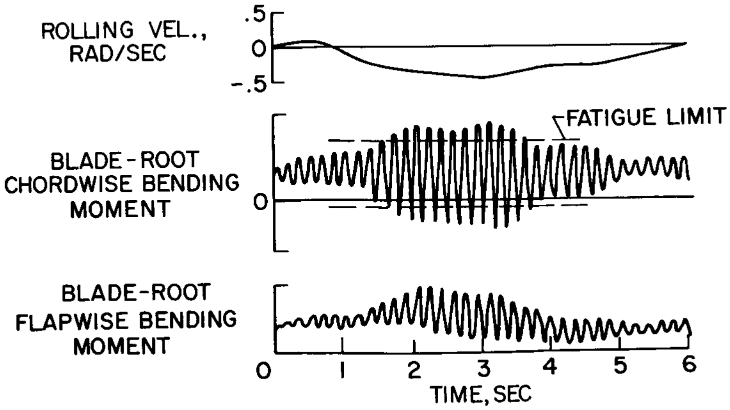


Figure 8



PENDULUM MODE
XH-51N FLIGHT IN GUSTY AIR AT 100 KNOTS

Figure 9



XH-13N STRUCTURAL BENDING MOMENTS
ROLL MANEUVER; V=70 KNOTS

Figure 10

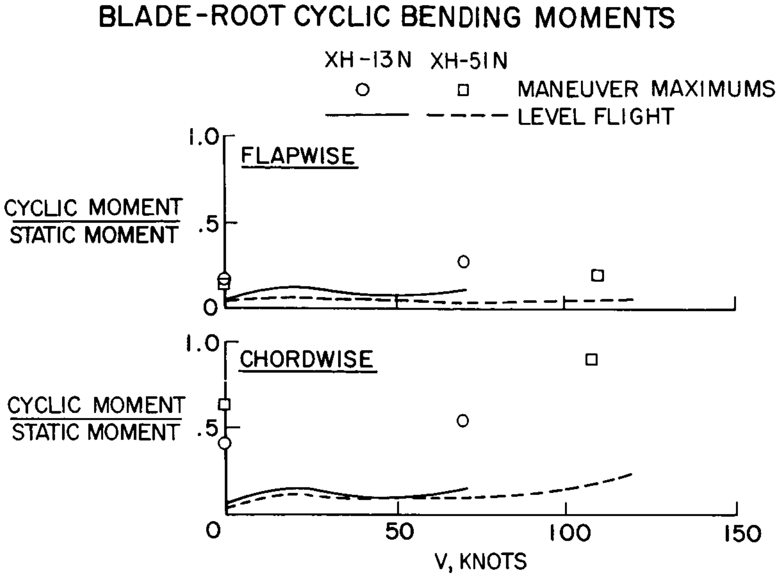
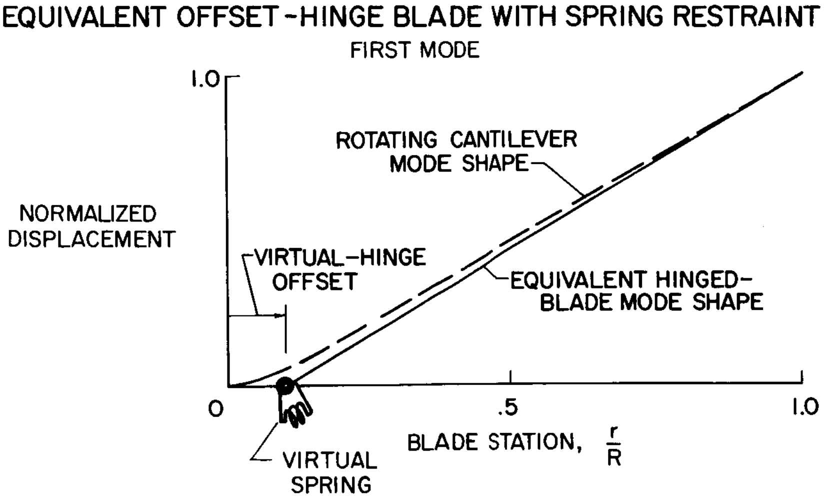

BLADE-ROOT CYCLIC BENDING MOMENTS

Figure 11


EQUIVALENT OFFSET-HINGE BLADE WITH SPRING RESTRAINT

FIRST MODE

Figure 12

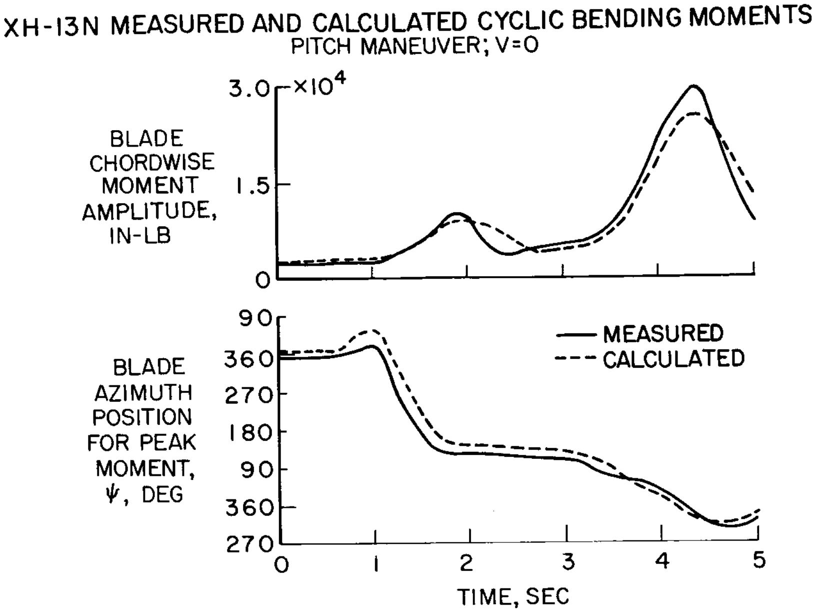


Figure 13

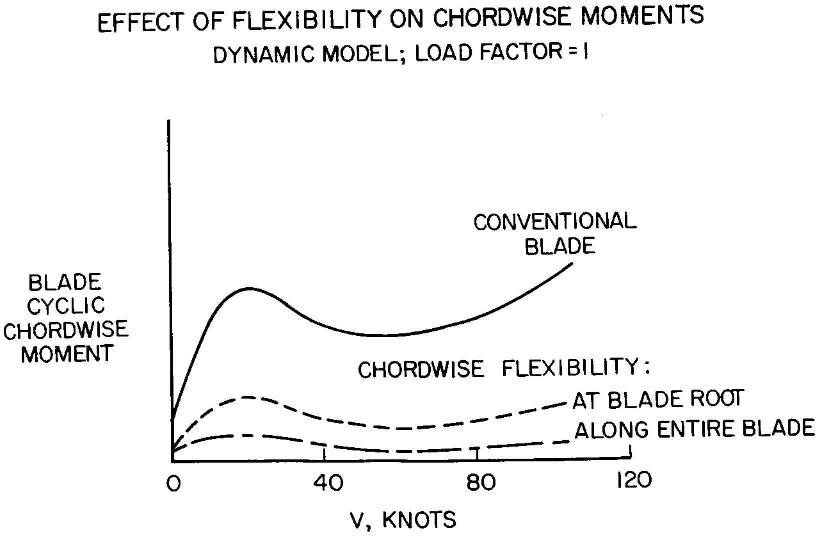


Figure 14